OPTIMAL BESS SIZING AND OPERATION SCHEDULING FOR A WIND FARM PARTICIPATING IN TURKISH ELECTRICITY MARKET

(TÜRKİYE ELEKTRİK PİYASASINA KATILAN BİR RÜZGAR ÇİFTLİĞİ İÇİN OPTİMAL BESS KAPASİTELENDİRMESİ VE OPERASYON PLANLAMASI)

by

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LIST OF SYMBOLS

ESS : Energy Storage System
BESS : Battery Energy Storage System
RES : Renewable Energy Source
YEKDEM : Renewable Energy Resources Support Mechanism
IRENA : International Renewable Energy Agency
ETKB : Republic of Türkiye Ministry of Energy and Natural Resources
EMRA : Energy Market Regulatory Authority
EXIST : Energy Exchange Istanbul
TEİAŞ : Turkish Electricity Transmission Corporation
DAM : The Day Ahead Market
MCP : Market Clearing Price
EMBSR : Electricity Market Balancing and Settlement Regulation
NREL : National Renewable Energy Laboratory
FiT : Feed-in tariff
SOC : State of Charge
DOD : Depth of Discharge
NIP : Negative Imbalance Price
PIP : Positive Imbalance Price
NLP : Nonlinear Programming
GAMS : General Algebraic Modeling System

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ABSTRACT

In today's electric system, where decentralization, democratization, and decarbonization are gaining in importance, battery energy storage systems (BESSs) are frequently used for intermittent energy sources such as wind and solar while participating in markets that have price fluctuations and imbalance costs. In this study, an onshore wind farm in Türkiye with an installed capacity of 24 MW that benefits from the Renewable Energy Resources Support Mechanism (YEKDEM) tariff is examined and an incentive scenario for renewables is suggested. Three market participation cases, Cases 1, 2, and 3, are analyzed for the farm. Case 1 represents participating in day ahead market (DAM) by leaving YEKDEM while Cases 2 and 3 represent participating in DAM with actual and suggested YEKDEM tariff, respectively. This thesis presents a nonlinear optimization model (NLP) including battery degradation cost to determine optimal BESS capacity and operation for different participation cases. Scenarios generated with various depth of discharge (DOD) limit values, determination methods of committed energy amount in DAM and BESS cost projections are solved by IPOPT solver in GAMS. According to obtained results, under current BESS cost, BESS integration increases farm’s profit compared to system without BESS for each market participation case. However, some scenarios are observed where farm’s profit cannot be increased with BESS. Considering the analyses, DOD limit value of 0.3 enhances profit more than other examined DOD limits. When profits obtained by BESS integration under same scenario for three participation cases are evaluated, Cases 3 and 2 yield the highest and lowest profit, respectively.

Keywords: Wind Farm, Electricity Market, BESS Sizing and Operation Scheduling, Battery Degradation Cost

ÖZET

Merkeziyetsizliğin, demokratikleşmenin ve karbonsuzlaştırmanın önem kazanıyor olduğu günümüz elektrik sisteminde, fiyat dalgalanmalarının ve dengesizlik maliyetlerinin mevcut olduğu piyasalara katılırken, batarya enerji depolama sistemleri (BESSs), rüzgar ve güneş gibi kesintili enerji kaynakları için sıklıkla kullanılmaktadır. Bu çalışmada, Türkiye'de 24 MW kurulu güce sahip olup Yenilenebilir Enerji Kaynakları Destekleme Mekanizması (YEKDEM) tarifesinden yararlanan bir karasal rüzgar çiftliği incelenmiştir ve yenilenebilir enerji için bir teşvik senaryosu önerilmiştir. Çiftlik için üç farklı pazar katılım durumu, Durum 1, 2 ve 3 analiz edilmiştir. Durum 1, gün öncesi piyasasına (GÖP) YEKDEM'den ayrılarak katılımı temsil ederken, Durum 2 ve 3, sırasıyla mevcut ve önerilen YEKDEM tarifesiyle GÖP'e katılımı temsil etmektedir. Bu tez, farklı pazar katılım durumları için optimum BESS kapasitesini ve operasyonunu belirlemek amacıyla batarya bozunma maliyetini içeren ve doğrusal olmayan bir optimizasyon modeli (NLP) sunmuştur. Çeşitli deşarj derinliği (DOD) sınır değerleri, GÖP'te taahhüt edilen enerji miktarını belirleme yöntemleri ve BESS maliyet projeksiyonları ile oluşturulan senaryolar GAMS IPOPT çözücüsü ile çözülmüştür. Elde edilen sonuçlara göre, güncel BESS maliyeti altında, BESS entegrasyonu, her pazar katılım durumu için BESS yokluğundaki sisteme kıyasla çiftliğin kârını artırmaktadır. Ancak, BESS ile çiftliğin kârının artırılamadığı bazı senaryolar da gözlemlenmiştir. Analizler dikkate alındığında, DOD sınır değerinin 0.3 olması, incelenen diğer DOD sınırlarına göre karı daha fazla arttırmaktadır. Üç katılım durumu için aynı senaryo altında BESS entegrasyonu ile elde edilen kârlar değerlendirildiğinde, Durum 3 ve Durum 2 sırasıyla en yüksek ve en düşük kârı sağlamaktadır.

Anahtar sözcükler: Rüzgar Çiftliği, Elektrik Piyasası, BESS Kapasite ve Operasyon Planlaması, Batarya Bozunma Maliyeti

1. INTRODUCTION

Energy systems have begun to evolve towards renewable energy sources in line with the targets of the Paris Agreement in 2015 to decrease greenhouse gas emissions for sustainability concerns (Hjalmarsson et al., 2023). Wind energy, which has a competitive Levelized Cost of Energy among renewables is considered as one of the major elements of the future energy mix. However, the intermittent nature of wind energy can cause stability issues in the grid and decrease financial efficiency. These challenges are the main obstacles to the wider spread of wind energy (Galli et al., 2024). Energy storage systems (ESSs) such as chemical, mechanical, electrical, and thermal ESS can be used in solving these technical and economic problems of wind power plants to ensure energy security and independence (Hjalmarsson et al., 2023). Battery energy storage systems (BESSs) have become popular as wind farm energy storage units due to the significant advantages they provide (He et al., 2024). Lithium-ion batteries are rapidly developing and preferred technology for wind farms as a result of their higher energy density compared to other batteries, low self-discharge level, and long life cycle. Although the cost of integrating a lithium-ion battery into a wind farm has decreased in recent years, it still requires notable expense. Therefore, it is crucial to determine the optimal size and operation for the BESS (Naemi et al., 2022). Nevertheless, this process is quite complicated as it depends on numerous economic and technical factors including battery degradation (Liu et al., 2020). This study first describes the Turkish electricity market dynamics and incentives of renewable energy sources in section 1. Then the studies related to BESS applications in power plants are reviewed in section 2. Operation of an onshore wind farm in Türkiye that participates in DAM within the YEKDEM is explained and a nonlinear model aims to maximize the farm's profit by BESS integration under the power plant, market, and BESS constraints is proposed in section 3. Optimization results for three different market participation cases are shared in section 4. Finally, the conclusion is provided in section 5.

1.1 Renewable Energy Sources (RESs)

Renewable energy sources, primarily driven by the intense radiation from the sun, are inexhaustible, easily producible, and sustainable resources that help reduce carbon emissions. They are highly important since they are environmentally friendly and play a role in reducing countries' dependence on external energy sources. Renewable energies include solar, wind, geothermal, hydraulic, biomass, wave, and hydrogen energy. The total installed capacity of renewable energy reached 3870 gigawatts (GW) worldwide in 2023, marking significant growth. In Türkiye, this capacity reached 58.4 GW, making it the 5th largest in Europe (IRENA, 2024).

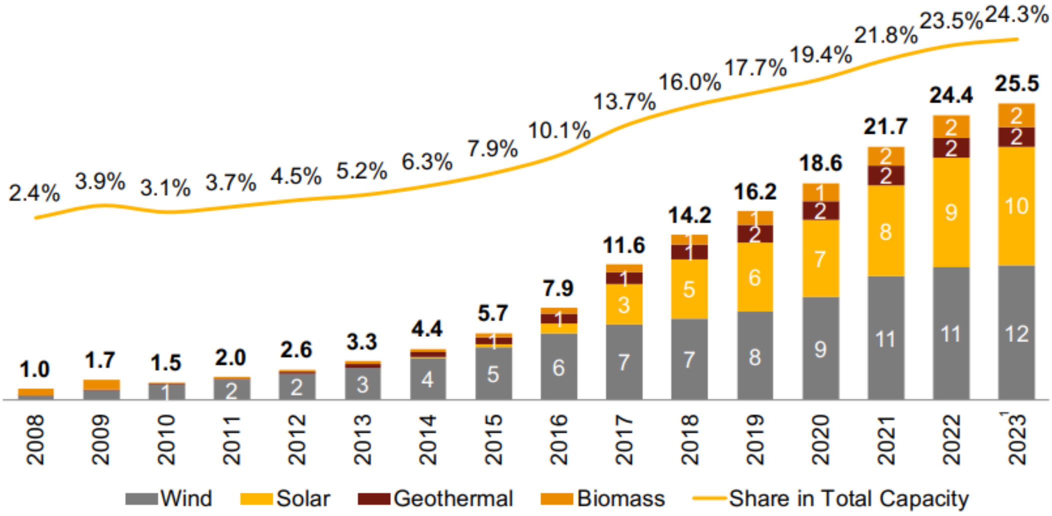

Figure 1.1.1: Installed capacity of RESs (2007-2023,GW) (PwC,2023)

The installed capacity of renewable energy sources in Türkiye, excluding hydroelectric power can be shown with the graph in Figure 1.1.1 over the years. In 2023, wind energy ranks first with the highest installed capacity. The source-based distribution of electricity generation in Türkiye for the year 2023 is illustrated in Figure 1.1.2.

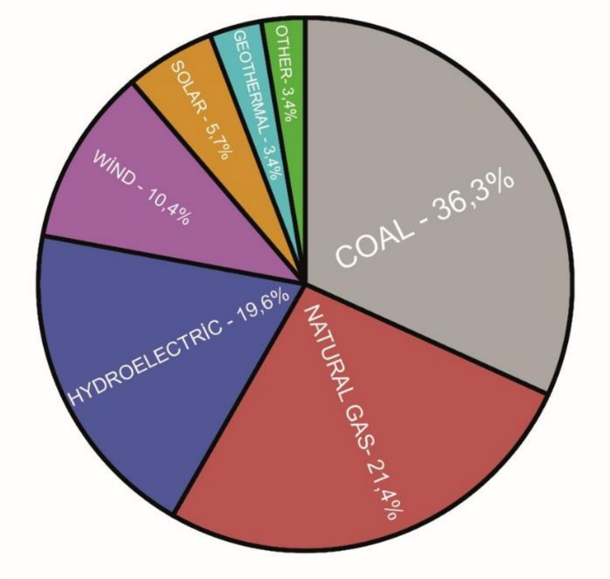

Figure 1.1.2: Türkiye's electricity generation in 2023 (ETKB, 2023)

1.2 Electricity Market and RES Incentives

Electricity, unlike many other commodities, cannot be stored in large scale for economic reasons and this necessitates the real-time management of energy markets. Energy markets are divided into spot and futures markets based on the timing of the transactions. Spot markets are the markets where a specific amount of goods and securities, and the money paid to acquire these assets, immediately change hands on the day the trade is made whereas futures markets are characterized by the trading of commodities or securities at predetermined prices and quantities agreed upon today with the actual delivery or cash settlement scheduled for a future date (Ruiz et al., 2012).

In Türkiye, EXIST as the market operator manages the organized energy market where a common price is established and trade occurs, while the system operator TEİAŞ is the party responsible for establishing the supply and demand balance in the energy system by monitoring system constraints and maintaining physical stability. Electricity is traded in Türkiye across financial and physical markets as it is shown in Figure 1.2.1. Physical markets are categorized into three types as bilateral agreements, organized markets, and real time markets. The market for bilateral agreements is a form of futures market where parties mutually set the terms, leading to a prior agreement on the price of electricity sales and report it to the market operator. Since 2018, particularly changes in the dollar exchange rate have reduced prices predictability, leading to a decrease in the number of bilateral agreements. Nevertheless, they still constitute a large portion of the overall market as it demonstrated in Figure 1.2.2 while most of them are short-termed (PwC,2023).

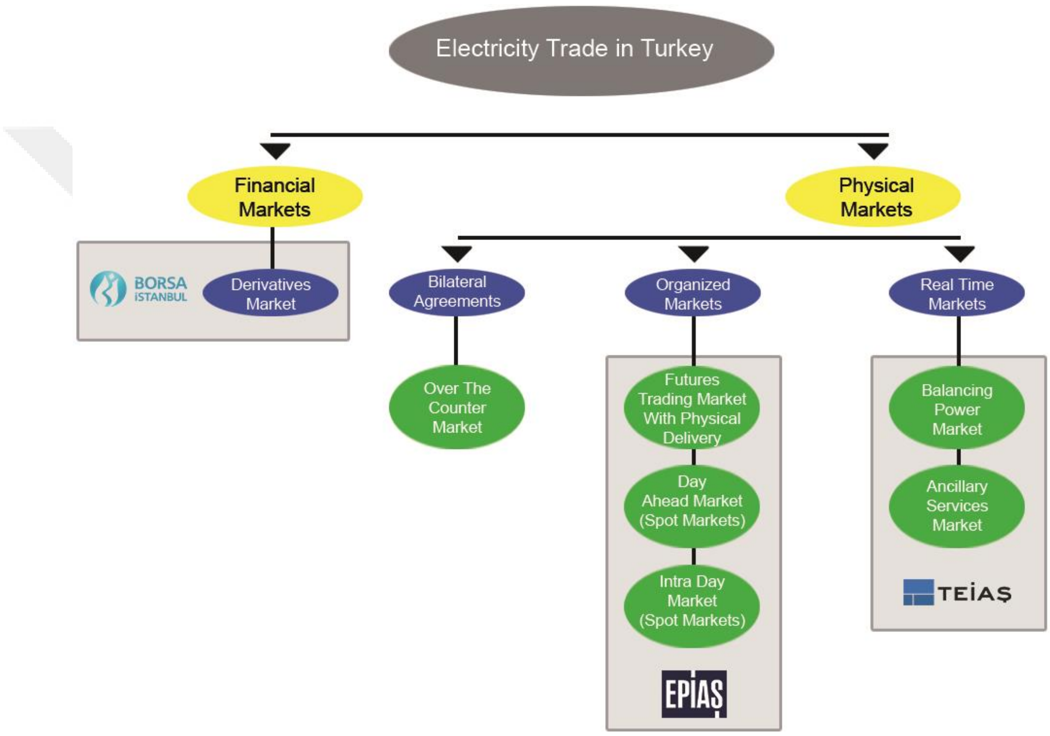

Figure 1.2.1: Turkish Electricity Market (EMRA, 2023)

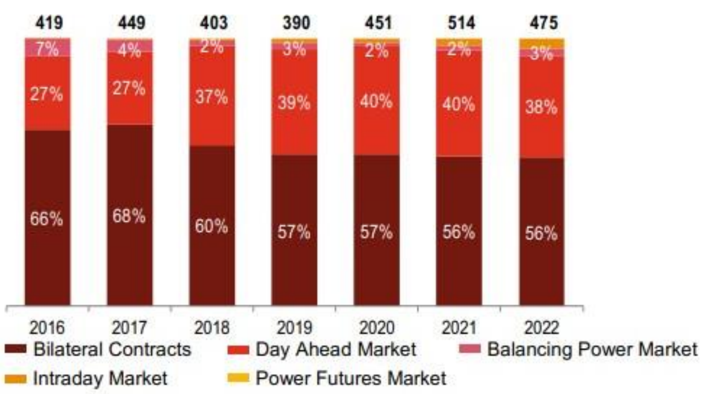

Figure 1.2.2: Electricity Market Volume (TWh)

Futures trading market, day ahead market and intra-day market compose the organized markets. EXIST initiated the futures trading market on 1 June 2021 that supports forward trading with physical delivery. This development aims to tackle the issue of unpredictability that hinders bilateral agreements in the market. Participants can transact directly with EXIST through the future trading market, eliminating the counterparty risks frequently seen in bilateral agreements. Its contracts differ from bilateral agreements, they are standard, and it is ensured that physical delivery and payments are secured. The day ahead (DAM) and intra-day markets are two types of electricity spot markets where participation is nonmandatory. In DAM, participants submit buying and selling quantities and price bids for each hour of the following day then by matching the offers from buyers and sellers, the hourly market clearing price (MCP) and the volume of transactions are established. MCP is considered as the reference price for other electricity markets. DAM is designed to ensure a balanced market one day ahead and simplify the system's operations. Bids of DAM are made using quantity in lots and price in Turkish Lira, respectively. (Lot: 1 MWh/10). (PwC, 2023). Typically, the intraday market opens after the DAM closes and trading for a specific hour can continue until a certain time before this hour in this market. The intraday market, where participants can trade to fulfill their requirements after the DAM closes, provides the balance between the DAM and the balancing power market. Prices naturally fluctuate even within an hour in the intraday market on the other hand, there is a uniform MCP for all transactions happening each hour of the following day in DAM (EMBSR, 2009).

The real time synchronization of the total electricity production and consumption is achieved through the power balancing market and its regulations obligate that balancing units capable of increasing or decreasing capacity by a minimum of 10 MW within 15 minutes are required to participate in the power balanced market. Services including primary and secondary frequency control, reactive power control, standby reserves, instantaneous demand control, black start, and regional capacity rental service are offered in ancillary service market to provide safe, real-time operation of networks. Electricity derivatives market where the purchase or sale of electricity derivative products occurs is operated by Borsa Istanbul in Türkiye (EMBSR, 2009).

Remarkably, Türkiye only utilized 15% of its onshore wind and 3% of its solar potential in 2021 (IEA, 2021). Although there has been an increase in these rates over the past few years, there is still a significant gap between Türkiye's renewable energy potential and its installed capacity. It is of great importance to integrate RESs into the energy system since Türkiye is dependent on foreign sources of energy. However, the high initial investment costs for renewable energy and the intermittent and not fully predictable nature of sources such as wind and solar reduce the investor interest in renewable energy projects. To address this issue and attract investor in renewable energy, like many countries, Türkiye has also established an incentive mechanism (Şenyapar et al., 2023). Depending on the development level of countries or renewable energy investments, different types of incentive mechanisms are implemented around the world, including feed-in tariff (FiT), premium-in tariff, mandatory quota and green certificate, tax exemptions and discounts, tender incentives, and investment incentives. In Europe, the most commonly used incentive mechanism is the FiT which provides a long-term purchase guarantee at a fixed price (Qadir et al., 2021).

Table 1.2.1: Initial YEKDEM FiT (YEK law, 2005)

RES	**Feed-in Tariff (USD/MWh)**	**Local Component Incentive (USD/MWh)**
Hydroelectric	73	10-23
Wind	73	6-37
Geothermal	105	7-27
Solar	133	4-56
Biomass	133	5-67

In Türkiye, purchasing guarantee for renewable energy was provided with the YEK law that came into force in 2005, and a ten-year fixed price promise were given in 2010 for power plants that produce energy from RESs within YEKDEM. This FiT is given in Table

1.2.1. It provided a purchase guarantee in USD and also offered local component incentives if the conditions were met. This tariff is valid for renewable energy power plants commissioned by 30 June 2021.

Due to the increased frequency of significant devaluation, YEKDEM switched to a tariff system denominated in Turkish Lira in 2021 (YEK law, 2005). Until this date, YEKDEM was attractive to producers, but the tariff change in that year resulted in a loss of its appeal. Hence, the most recent YEKDEM participant list is predominantly composed of facilities that continue to benefit from the initial YEKDEM tariff. The prices are set at 1730.4 TL/MWh for onshore wind power plants and 2040.6 TL/MWh for wind or solar power generation plants with electricity storage facility, in the updated YEKDEM tariff announced in May 2024. These amounts are below the 73 USD/MWh offered for wind energy in the first YEKDEM tariff guarantee (EXIST,2024).

1.3 Electricity Storage Activities

Classification of different ESSs is shown in Figure 1.3.1. The accelerated transition to renewable energy sources has increased interest in energy storage systems and electrolyzers to manage the intermittent nature of these sources and gain flexibility. Türkiye Energy Market Regulatory Authority (EMRA) announced the Electricity Storage Regulation, which was developed based on the system needs, in May 2022. Over 275 GW of storage capacity applications were submitted to EMRA as of June 2023. The most obvious reason for this situation is that, according to the legislation, firms that establish a storage unit can also construct wind or solar power plants with the same capacity of this unit (PwC, 2023). However, examining the economic viability of these storage units, which allow firms to take advantage of arbitrage opportunities and reduce imbalance costs, is crucial before making installation decision especially for the firms that do not want a storage unit just to be able to install additional power plant capacity or get a license for a new power plant.

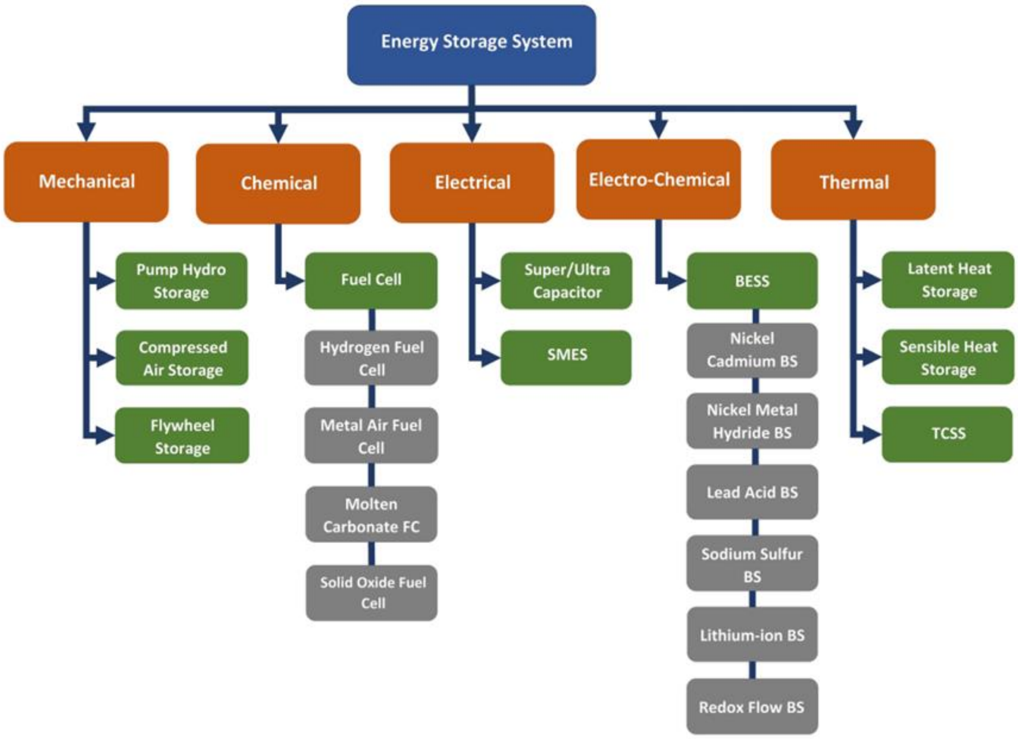

Figure 1.3.1: Classification of ESSs (Rana et al., 2023)

2. LITERATURE REVIEW

ESSs play a crucial role in power systems as they offer the opportunity to use the energy stored in various forms by converting it into electrical energy when required. Several outstanding attributes, including availability, adaptability, flexible operation, rapid response, modularity, etc., enhance the appeal of ESSs for power system applications (Choudhury, 2022). Rana et al. (2023) provided a summary of a comparative analysis to identify the suitable ESS for power system applications, along with a review of how various ESSs are implemented globally, highlighting their appropriateness for these applications. This analysis also illustrated the characteristics of different ESSs, including their benefits and drawbacks. Tan et al. (2021) presented a review of ESS technology such as battery, thermochemical, thermal, pumped energy storage, compressed air, hydrogen, chemical, and magnetic energy storage. In this study, ESS integration for renewable energy sources to deal with their intermittent nature was particularly examined. Deguenon et al. (2023) offered an in-depth analysis of electrochemical BESSs such as lead acid, lithium-ion, sodium-sulfur, sodium-chloride, nickel-cadmium, and flow batteries, detailing their features, applications, and technologies appropriate for use on a grid scale. They emphasized that lithium and flow batteries are the predominant technologies in use and the integration of batteries into the power grid could facilitate reaching a penetration rate of 40–50% of fluctuating renewable energies. Eskandari et al. (2022) classified BESSs applications in microgrids into five categories considering their time constants. These categories were synthetic inertia response (0~1 s), primary frequency support (1~60 s), covering intermittent renewables (1~15 mins), economic programs for steady-states (15~60 min), and slack bus realization (0~60 mins).

Li-ion batteries are the most widely used and advanced battery storage technology for grid applications, comprising over 90% of the global market (Borhani, 2019). Utilizing a li-on BESS offers various advantages, including high energy density, an extended lifecycle, low self-discharge rate, high cell voltage, etc. (Wali et al., 2022). The cost of lithium-ion battery packs is anticipated to fall from approximately $200/ kWh to $70/kWh by 2030 consequently the installed Li-ion BESS capacity is expected to grow steadily (Deguenon et al., 2023).

In recent years, there has been a notable rise in the integration of large-scale wind farms and BESSs. This trend is driven by the benefits these technologies offer in compensating for wind power intermittency and solving the problems related to power market participation and prediction error (Hauer et al., 2020). Nonetheless, the significant investment cost of BESS integration and the ambiguity surrounding the integration project's profitability remain major barriers to the widespread adoption of BESS in wind farms. Even though optimization of BESS design and operation is capable of solving profitability issues, this optimization is highly challenging due to several dynamics such as battery degradation (Zhang et al., 2021).

As one of the BESS applications in wind farms Luo et al. (2015) introduced a novel operational BESS dispatch strategy to mitigate wind power fluctuations more effectively by switching the referenced power output of the wind farm between optimistic and pessimistic forecast scenarios. They also determined the BESS capacity with historical wind data. Zhang et al. (2017) presented a new control and sizing scheme of BESS in wind farms for wind smoothing. In their study, it was stated that by reducing the frequency of charging/discharging switches and preventing over-discharge, this control and sizing scheme can effectively safeguard the BESS, thereby extending its lifespan. The BESS placement issue is handled by neither of this previous research but a random placement of BESS may result in significant energy losses in some cases. Accordingly, the literature does not only include studies on BESS size and operational optimization but also there are numerous works concentrating on optimal BESS placement (Chreim et al., 2024). Zhang et al. (2016) used a stochastic optimization approach to determine the optimal location and size of BESS in the distribution network. In their study, the Monte Carlo simulation was utilized to simulate the uncertainties in wind power output and system load, and a stochastic optimization model with chance constraint was developed to find the optimal siting and capacity of BESS while guaranteeing a certain degree of wind power utilization. Zhang et al. (2024) improved a strategy for optimal sizing and placement of BESS in power systems with high wind penetration, regarding the coordinated frequency and voltage control. The suggested strategy outperformed the traditional allocation techniques in terms of frequency and voltage control performance while requiring a lower BESS investment cost.

It is possible to categorize the previous studies related to the integration of BESSs into wind farms as non-market and market research. Analyzing the optimal technical performance of BESS on a small, isolated grid or addressing specific technical needs are generally the goals of non-market studies. Conversely, market studies typically explore how BESSs engage in wholesale electricity markets, focusing on either solely the energy market or both the energy and ancillary services markets (Naemi et al., 2022). As an example of non-market research Shi et al. (2023) developed an advanced biogeography-driven optimization algorithm that adjusts migration rates according to habitat suitability indexes and differential perturbations to optimize the operation and capacity of BESSs in microgrids that harness wind energy. They minimized the total operational cost of the microgrid (MG) to determine the optimal battery capacity and aimed to improve reliability and lower costs, taking into account the intermittent and unpredictable characteristics of renewable energy resources. Lobato et al. (2022) introduced an economic analysis tool developed to assess the feasibility of integrating a battery energy storage system (BESS) with renewable power plants for various market scenarios including day-ahead price arbitrage, participation in the balancing market, and schedule tracking. They examined the economic viability of varying Li-ion and vanadium-redox BESS capacities using a 30 MW wind farm that was involved in the Spanish electricity market. This study is among the market research.

State of charge (SOC) is the ratio of available battery capacity for discharge to battery rated capacity and it can be between 0% and 100%. Depth of discharge (DOD) is defined as the discharged percentage of battery rated capacity (Ahmadian et al., 2018). Energy transfer within the battery lead to cell degradation, ultimately resulting in the battery capacity loss (Vetter et al., 2005). Although the aging process of batteries is intricate, it can be assumed that the primary factor influencing degradation is the depth of discharge (Lee and Kim, 2022). In many existing studies, degradation was not considered when sizing and operating grid scale BESS. As one of them Salman et al. (2020) examined battery size needed to sustain a stand-alone microgrid and a grid-connected microgrid for a whole year in light of the hourly wind power potential. Their goal was minimizing the operational cost of microgrid, they used NLP and LP model for different scenarios they investigated, and GAMS software was utilized for optimization.

There are numerous studies in the literature that address battery degradation with different approaches for BESS application with wind energy. Some of these reviewed studies and their optimization methods can be clarified as follows, a special metaheuristic algorithm known as the contracted fitness-dependent optimizer (CFDO) was presented by He et al. (2024). Optimizing the size and operation of BESSs in microgrids powered by high wind energy penetration was the main goal of this study. The CFDO algorithm considered DOD of battery and showed outstanding performance in finding optimal solution. Optimal battery increased system efficiency and reduced costs compared to the situation without a battery while extended battery life thanks to operation in recommended DOD range. Gholami et al. (2022) used a statistical approach taking into consideration spatial smoothing, wake effect, and turbulence for the analysis and estimation of fluctuations in wind farm power. They proposed an LP model to determine the optimal battery capacity while minimizing the total cost consisting of battery cost and deviation cost. They provided a novel method to estimate the battery lifetime under the non-uniform charge/discharge cycles. This method had an important role for their cost function definition. Alharbi et al. (2022) introduced a grid-scale BESS-sizing optimization model designed to find the optimal capacity and schedule of lithium-ion batteries. This MILP model aimed to accurately forecast long-term revenue by taking into consideration life cycles, degradation costs, and discharge rates when determining the size and operation of a BESS for grid applications and utilized frequency regulation and energy arbitrage to generate revenue.

This study aims to compare different market participation cases for a wind farm in the presence of a BESS when optimal capacity and operation is determined to maximize the profit of the farm. Therefore, a nonlinear model is developed according to dynamics of the Turkish electricity market and relevant regulations by using BESS, power plant and market constraints. This model considers battery degradation cost and can analyze the effect of various battery DOD limits on the profit. To the authors knowledge, there is no other research which uses same system structure, model objective or constraint set as this study to compare different market participation cases for a wind farm participating in Turkish electricity market.

3. MATERIALS AND METHODS

3.1 Problem Definition and Data Set

In electricity markets characterized by significant price fluctuations and imbalance costs, it is possible for the plants generating electricity from intermittent RESs such as wind and solar to increase their profitability through BESS integration. However, it is of great importance to analyze the economic viability of BESS projects, which have high investment costs. In this study, an onshore wind farm in Türkiye with an installed capacity of 24 MW is examined. This wind farm, which continues to benefit from the initial YEKDEM tariff offering a purchase guarantee of 73 USD/MWh for wind energy, participates in the DAM by using wind generation forecasts when submitting sales bids for the following day in this market. These forecasts are obtained by first making wind speed predictions and then determining the theoretical production amount using the power conversion curves of the turbines. Although the accuracy of generation forecasts has improved in recent years thanks to advanced system simulations and AI-supported new algorithms, it is not perfect due to being influenced by many different parameters (Huang et al., 2024). In this study, the committed energy amount of the farm for a settlement period t in the DAM is assumed to equal to the sales volume that the farm bid previous day for this period. The revenue of the farm in the DAM is determined by Equation 3.1.

$$(P_t^{com} \times d_t^A) - \left(C_t^{nip} \times P_t^u\right) + \left(C_t^{pip} \times P_t^s\right) \tag{3.1}$$

Where P_t^{com}, d_t^A, C_t^{nip}, C_t^{pip}, P_t^u and P_t^s are committed energy generation , MCP (\$/MWh), negative imbalance price (NIP) (\$/MWh), positive imbalance price (PIP) (\$/MWh), unsatisfied committed energy amount and energy surplus exceeding the committed energy amount at a settlement period t (hour), respectively. Payments under DAM and YEKDEM are made in TL for each settlement period. Since the analysis in this study is conducted in USD, these payments are calculated in USD using the exchange rate at the related settlement period t. Negative imbalance occurs when the plant delivers less energy to the grid than the contracted energy amount for a settlement period t, while positive imbalance occurs when more energy than the contracted amount is delivered to the grid. These imbalance prices are calculated with Equations 3.2 and 3.3.

$$C_t^{nip} = max\{SMP_t , d_t^A\} \times (1 + k) \tag{3.2}$$

$$C_t^{pip} = min\{SMP_t , d_t^A\} \times (1 - n) \tag{3.3}$$

SMP_t (\$/MWh) is the system marginal price established based on balancing power market operations for a settlement period t, k and n are imbalance-related coefficients determined to be 0.03. The payment for the YEKDEM tariff is shown by Equation 3.4.

$$P_t^G \times [YEK - (d_t^A \times j)] \tag{3.4}$$

YEK, j ve P_t^G are YEKDEM FiT price (USD/MWh), tolerance coefficient for wind energy and, the amount of energy injected to the grid by the plant during the settlement period t, respectively. When the amount in the equation 3.4 is positive, a payment is made to the plant, while if it is negative, the plant makes a payment to the market operator. Since the frequency of MCP exceeding the YEKDEM tariff price has increased, particularly over the past year, it has been the subject of investigation how the farm's profit is affected by participating in DAM without YEKDEM. This increasing frequency can lead producers to consider leaving YEKDEM, as is the case currently and it also makes joining YEKDEM less efficient for the plants that are not already participants. In this study, an incentive scenario is used to address such issues and make YEKDEM more attractive to producers and investors, with the aim of increasing renewable energy investments and the analyses are repeated for this incentive scenario as well. Unlike the actual YEKDEM tariff, an upper limit is determined for MCP and in the settlement periods when MCP is less than or equal to this upper limit, if a negative result is obtained with equation 3.4, the plant's obligation to make the payment to the market operator is eliminated in this incentive scenario. In the settlement periods where MCP is above this upper limit, when equation 3.4 results in a negative value, only the portion exceeding the YEKDEM income that can be obtained with the upper limit is paid to the market operator. If a positive result is obtained with equation 3.4 for a settlement period, this amount is paid to the plant as it is in the actual YEKDEM tariff.

In this study, the impact of integrating BESS into the wind farm on the farm's profitability is analyzed for three different market participation cases compared to the situation without BESS. These cases are as follows,

Case 1: Participating DAM by leaving YEKDEM

Case 2: Participating DAM with the actual YEKDEM tariff

Case 3: Participating DAM with the suggested YEKDEM tariff

Within the scope of the study, hourly forecasted and actual power generation data from an onshore wind farm with an installed capacity of 24 MW are collected over a 7-month period, from the beginning of July to the end of January of the following year. The hourly MCP, NIP, and PIP data to be used in the analyses are obtained by EPIAŞ transparency platform for the period from 01.07.2023 to 31.01.2024. The battery selected for integration analysis is a Li-FePO4 (lithium-iron-phosphate) battery. The cost of BESS technologies is assessed using four different components. Two of these are associated with the BESS energy capacity: the capital cost for the battery packs and the construction and commissioning cost ($/kWh). The other two are associated with the BESS power capacity: the power conversion system and balance of plant cost ($/kW). These costs are determined using the 2023 Annual Technology Baseline report from the National Renewable Energy Laboratory (NREL, 2023).

3.2 Methodology

The structure that is formed when BESS is integrated into the wind farm is depicted in Figure 3.2.1. In this paper, a 7-month period for which we have perfect information about real data is considered, and it is examined how the farm's profit could have been shaped under different market participation cases if a BESS had been present during this period.

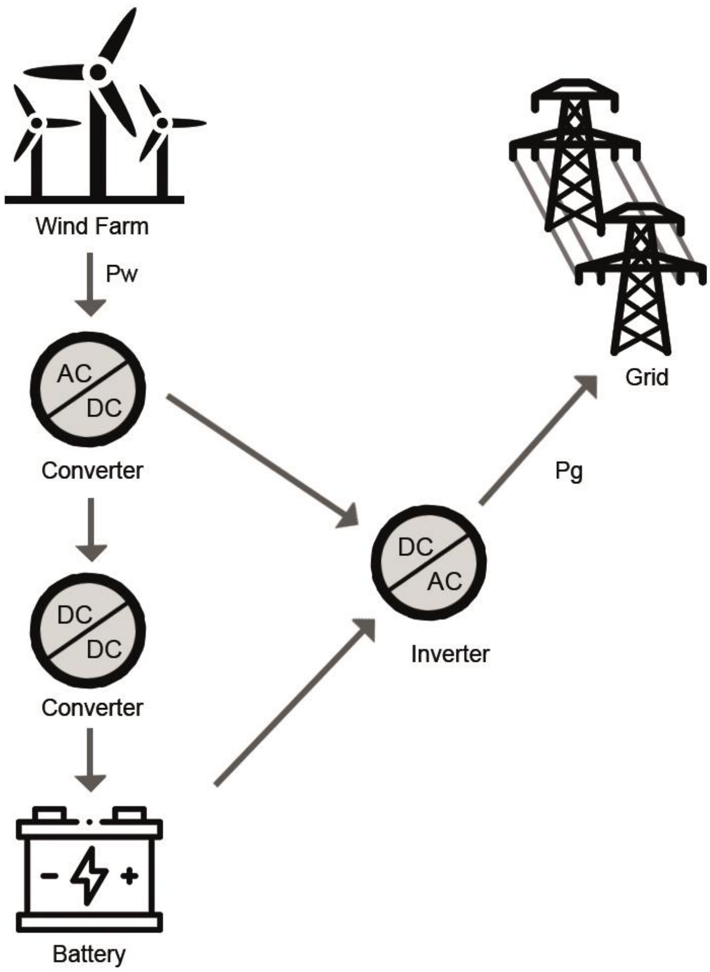

Figure 3.2.1: The system architecture

Factors such as depth of discharge, the average state of charge (SOC) of each cycle and the average cell temperature cause battery cycling aging which results in loss of storage capacity. A li-ion battery is generally considered at the end of its useful life when its capacity declines to less than 80% of its initial value (Yang et al., 2022). The cycle life indicates the maximum number of full cycles a battery can undergo before reaching the end of its useful life. The battery cycle life and DoD relationship for a li-ion battery is defined by Equation 3.5 where N_O represents the number of cycles per full DOD, as experimental paremeters N_O, β_1 and β_2 are 2731, 0.679 and 1.61, respectively (Mallon et al, 2017).

$$N_{cycle} = N_O \times DOD^{-\beta_1} \times e^{\beta_2 (1-DOD)} \tag{3.5}$$

Table 3.2.1: Variables, indices, and parameters of the proposed model

Indices and Parameters	
t, τ ∈ T	Index of time intervals
$\boldsymbol{l}$	Analysis horizon [day]
$\mathbf{C^b{}_p}$	BESS project cost associated with power capacity [$/MW]
$\mathbf{C^b{}_E}$	BESS project cost associated with energy capacity [$/MWh]
$\boldsymbol{\beta}$, $\boldsymbol{\eta^c}$, $\boldsymbol{\eta^d}$	Self-discharge, charge, and discharge efficiencies for the BESS
$\boldsymbol{\eta^g}$	Efficiency for energy delivered to the grid without using the battery
$\mathbf{P_t^W}$	Wind generation at time t [MW]
$\mathbf{P^F{}_t}$	Forecasted wind generation at time t [MW]
$\mathbf{C_t^{nip}}$	Negative imbalance price at time t [$/MWh]
$\mathbf{C_t^{pip}}$	Positive imbalance price at time t [$/MWh]
$\mathbf{d_t^A}$	Day-ahead market price in energy market at time t [$/MWh]
$\mathbf{Y^{sp}{}_t}$	Multiplier related to YEKDEM tariff at time t [$/MWh]
dr	Interest rate

Δt	Time resolution [1 hour]
r_{min}	Minimum allowed state of charge level of the battery
r_{in}	Initial state of charge level of the battery
m_u, m_l	Maximum and minimum allowed ratio of the committed energy amount to the forecasted wind generation (after loss)
DOD	Dept of discharge limit (upper limit)
RRV	Ratio of the BESS residual value at the end of its useful life to the BESS project cost
WFP	The installed power capacity allocated to the wind farm's license [MW]
N_{cycle}	Battery cycle life for the specified DoD
MCAP	Upper limit for the rated energy capacity of the battery
	Variables
P^b_{max}	Rated power of the battery [MW]
E^b_{max}	Rated energy capacity of the battery [MWh]
P_t^c	The charged power into the BESS at time t (before the losses) [MW]
P_t^d	The discharged power by the BESS at time t (after the losses) [MW]
P_t^u	Unsatisfied committed energy amount at time t [MW]
P_t^s	Energy surplus exceeding the committed energy amount at time t [MW]
P_t^{com}	Committed energy amount to injected to grid at time t [MW]
P_t^G	Energy injected to grid at time t [MW]
E^b_t	Battery energy level at the beginning of time t [MWh]
E_{total}	Battery lifetime throughput for specified DOD [MWh]
C_T^b	BESS project cost [$]

The objective function;

$$\text{Max } \sum_{t=1}^{24l} (P_t^{com} \times d_t^A) - (C_t^{nip} \times P_t^u) + (C_t^{pip} \times P_t^s) + (P_t^G \times Y_t^{sp}) - \frac{[C_T^b - C_T^b \times RRV \times (1+dr)^{-l}] \times (P_t^c \Delta t\, \eta^c + P_t^d \Delta t\, /\eta^d)}{E_{total} \times 2} \tag{3.6}$$

Subject to;

$$C_T^b = C_p^b \times P_{max}^b + C_E^b \times E_{max}^b \tag{3.7}$$

$$m_l \leq \frac{P_t^{com}}{(P_t^F \times \eta^g)} \leq m_u \tag{3.8}$$

$$P_t^G = (P_t^W - P_t^c)\eta^g + P_t^d \tag{3.9}$$

$$P_t^{com} + P_t^s - P_t^u = P_t^G \tag{3.10}$$

$$P_t^G \leq \text{WFP} \tag{3.11}$$

$$P_t^c \leq P_t^W \tag{3.12}$$

$$P_{max}^b \leq E_{max}^b \tag{3.13}$$

$$P_t^c \times \eta^c \leq P_{max}^b \tag{3.14}$$

$$P_t^d / \eta^d \leq P_{max}^b \tag{3.15}$$

$$E_{t+1}^b = \beta\, E_t^b + P_t^c\, \Delta t\, \eta^c - P_t^d\, \Delta t\, /\eta^d \tag{3.16}$$

$$E_{max}^b \times r_{min} \leq E_t^b \leq E_{max}^b \times (r_{min} + DOD) \tag{3.17}$$

$$E_1^b = E_{max}^b \times r_{in} \tag{3.18}$$

$$E_{total} = N_{cycle} \times DOD \times E_{max}^b \tag{3.19}$$

$$\sum_{t=1}^{24l} \frac{P_t^d \Delta t}{\eta^d} \leq E_{total} \tag{3.20}$$

$$\sum_{t=1}^{24l} P_t^c \Delta t\, \eta^c \leq E_{total} \tag{3.21}$$

$$0 \leq E_{24l+1}^b \leq E_{max}^b \tag{3.22}$$

$$P_t^{com} \leq \text{WFP} \tag{3.23}$$

$$E_{max}^b \leq MCAP \tag{3.24}$$

$$0 \leq P_{max}^b, P_t^{com}, P_t^s, P_t^u, P_t^G, P_t^c, \; P_t^d, C_T^b \;, E_t^b \;, E_{total} \qquad 0 < \; E_{max}^b \tag{3.25}$$

Variables, indices, and parameters of the proposed model are given by Table 3.2.1. The objective function in Equation 3.6 is established to maximize the li-ion BESS integrated wind farm profit consists of day-ahead market participation, YEKDEM tariff and battery degradation cost components. BESS project cost is calculated with Equation 3.7. In this model, 1 hour is selected as time resolution. When the generated energy is supplied to the grid without using the battery, a loss still occurs. For a settlement hour t, with generation forecast available, the committed energy amount is determined by considering this loss. Constraint 3.8 restricts the ratio of the committed energy amount to the forecasted wind generation (after loss) with maximum and minimum allowed levels. The energy supplied to the grid at hour t is obtained by Equation 3.9 and the unsatisfied committed energy amount or energy surplus exceeding the committed energy at hour t is determined with Constraint 3.10. The amount of energy that a power plant with integrated electrical storage unit can supply to the grid during the settlement period t cannot exceed the production amount that can be achieved with the installed power capacity recorded in the facility's license. Constraint 3.11 ensures this condition. Constraint 3.12 indicates that the charged power into the BESS (before the losses) should be less than or equal to wind power generation. The relationship between the rated energy capacity and the rated power of battery is set by Constraint 3.13. Constraints 3.14 and 3.15 restrict the charged and discharged power, respectively by considering battery rated power. The change in the battery energy level is achieved with Equation 3.16. The battery energy level is limited to a certain range by Constraint 3.17 to prevent the battery from rapidly ageing and this constraint ensures that depth of discharged or charged energy in each cycle whether the cycles are uniform or nonuniform, is less than or equal to DOD limit. Equation 3.18 determines the initial battery energy level. Battery lifetime throughput for specified DOD is calculated with Constraint 3.19. Total discharged and charged power are limited by Constraints 3.20 and 3.21, respectively. Battery energy level at the end of the analysis horizon is restricted with Constraint 3.22. Constraint 3.23 restricts the committed energy amount of the farm for a settlement period t to be less than or equal to WFP. Battery rated energy capacity must be applicable for the farm, Constraint 3.24 ensures this condition.

In the structure where the BESS is not integrated into this farm, the efficiency for energy delivered to the grid is still η^g . It is important to determine r_{in} and r_{min} in a way that does not violate the model constraints, when β takes a positive value less than 1 this determination process becomes more precise. The committed energy amount of the farm for a settlement period t in the DAM is assumed to equal to the sales volume that the farm bid previous day for this period . Installed power capacity recorded in the facility's license represents the maximum power generation that the farm can carry out so the forecasted wind generation is less than or equal to this capacity. m_l is determined as an appropriate value to not violate Constraint 3.23. DAM payments are made 2 days after the date the energy is supplied to the grid, while payments related to imbalance and YEKDEM occur in the 3rd week of the following month. The time value of money is not considered for these cash flows in the analysis as it makes the model overly complex. While examining Case 1, all Y_t^{sp} values are zero along the analysis period. When switched to Case 2 analysis, Y_t^{sp} values can change and they are determined based on actual YEKDEM tariff. For Case 3, Y_t^{sp} values are established by suggested incentive scenario. In reality, P_t^u and P_t^s cannot be positive values simultaneously for any settlement period t. However, there is no need to assign a binary variable to model this situation. Within the framework of the current market dynamics, two different situations may occur: either C_t^{pip} is a non-negative value while C_t^{nip} is greater than it, or C_t^{pip} and C_t^{nip} are both zero for the time t . Since the goal is to maximize Equation 3.6, in the first situation, the model solution tends not to assign positive values to both P_t^u and P_t^s simultaneously at time t thus only one of them can be positive. For the second situation, it is not important if the solution assigns positive values to both P_t^u and P_t^s simultaneously at time t, as this does not affect the profit amount and does not cause a deviation from reality. It is not desired for the battery to be charged and discharged at the same time in a settlement period t, thanks to the nature of the presented system, using a binary variable is not necessary to achieve this. When the generated energy goes to the battery and then supplied to the grid by it, this energy suffers more losses compared to being directly supplied to the grid without using the battery. Additionally, battery usage also incurs a cost. Due to the maximization of profit as the objective and the nature of the imbalance prices, the model solution tends not to give positive values to P_t^c and P_t^d simultaneously at time t.

While finding the battery cycle life and DOD relationship for the li-ion batteries, for each cycle battery SOC level is reduced to (1-DOD) from the fully charged state and then battery is fully charged for the experiment, but in our model, for specified DOD limit and r_{min} battery SOC level can change in the interval between r_{min} and (r_{min}+DOD) and depth of discharged or charged energy in each cycle whether the cycles are uniform or nonuniform, is less than or equal to DOD limit, but these differences with the experimental conditions are not considered since with the model assumptions, the battery SOC level can be kept at healthier ranges for the battery compared to SOC level between 1 and (1-DOD) in the experiment and the charge and discharge depth is allowed to remain below DOD limit, that may affect battery lifetime throughput better compared to cycles with DOD.

4. RESULTS

The self-discharge rate of li-ion batteries ranges between 2% and 1% per month (Battery University, 2021). Since this rate is not high, battery self-discharge efficiency is assumed to be 1 in the analyses. As the interest rate for USD is quite low, it is assumed to be 0. For the case 3 upper limit of MCP to use at the suggested incentive scenario is determined as 103$.

Table 4.1: Data set for the analysis

Parameter	Value	Parameter	Value
l	215	η^g	0.9
C_p^b	388 000	m_l	0
C_E^b	372 000	RRV	0.35
β	1	WFP	24
η^c	0.9	dr	0
η^d	0.95	Δt	1

MCP has a fluctuating nature in the current market, but its fluctuation does not affect each market participation case to the same extent. Since there is a fixed price purchase guarantee in Case 2, the impact of MCP on its profit is less compared to other cases and, when no imbalance occurs, this impact is only due to the tolerance coefficient for Case 2. In Case 3, when there is no imbalance, the effect of MCP on its profit depends on the determined upper limit of MCP for suggested incentive scenario and the tolerance coefficient. In the current market dynamics, considering the three cases, the impact of

MCP fluctuations on profit is greatest in Case 1 and least in Case 2. When an imbalance occurs in each of the three cases, MCP further impacts profit by imbalance costs.

$$P_t^{F\prime} = P_t^F \times \eta^g \tag{4.1}$$

$$P_t^{W\prime} = P_t^W \times \eta^g \tag{4.2}$$

Table 4.2: Profit in the different scenarios for the wind farm in the absence of a BESS

	$\boldsymbol{P_t^{com} = P_t^{F\prime}}$	$\boldsymbol{P_t^{com} = P_t^{W\prime}}$
Case 1	3 367 073	3 463 874
Case 2	3 337 406	3 434 207
Case 3	3 659 031	3 755 833

$\boldsymbol{P_t^{F\prime}}$ is obtained with multiplying the farm's forecasted generation $\boldsymbol{P_t^F}$ by the efficiency value for the energy supplied to the grid without using the battery, this efficiency value is same for both BESS integrated farm structure and farm without BESS. $\boldsymbol{P_t^{W\prime}}$ is also calculated by multiplying this efficiency value with the actual wind generation $\boldsymbol{P_t^W}$. $\boldsymbol{P_t^{F\prime}}$ and $\boldsymbol{P_t^{W\prime}}$ are determined with Equation 4.1 and 4.2, respectively. The wind farm participates the electricity market in the absence of a BESS by determining a committed energy amount equal to its forecast $\boldsymbol{P_t^{F\prime}}$ since it can not store energy to use at the appropriate time. Second column of Table 4.2. represents the profit of the wind farm in this situation when it participates electricity market under different scenarios in the absence of BESS for a 7-month analysis period. The third column gives the profit that would have been made if the farm had accurately forecast wind generation amount. The difference between the two columns is due to imbalance costs and in each case, the farm gives all the energy it generates to the grid. It is observed that the most advantageous situation occurs under the suggested incentive scenario, and participating in the DAM by leaving YEKDEM is more profitable for the analysis period compared to the market participation with the actual YEKDEM tariff. Even when the upper limit set for MCP in Case 3 is reduced to a level that equalizes the profit of Case 1 and Case 3, YEKDEM may be more attractive than participating in DAM without YEKDEM for the producers.

To prevent the rapid aging of a lithium-ion battery, its charge level should be kept between 20% and 80% (Galli et al., 2024). Therefore, analyses are conducted for different DOD limit values of 60% and below in this study. NREL estimates that by 2030, BESS costs will reduce 47%, 32% and 16% in its low, mid and high cost projections, respectively (NREL, 2023). So the analyses are repeated with these costs to investigate the profitability of BESS integration project in the near future by assuming that the current market and generation conditions are maintained. According to experimental data, a Li-ion battery that typically maintains a state of charge between 30% and 50% has a longer lifespan compared to those that frequently remain between 70% and 90% or 20% and 40% (Galli et al., 2024). However, in our model, changing the $\boldsymbol{r_{min}}$ value for any specified DOD limit has no effect on the battery life, this situation is not modeled. Using the optimal $\boldsymbol{r_{min}}$ value for the specified DOD limit in our analyses just enables an operation scheduling that is better for battery health in real life application. Therefore, while in the last part of our analyses, where the results are shared related to BESS operation scheduling, $\boldsymbol{r_{min}}$ is determined as better value for battery health and the scheduling is carried out accordingly, in the first part of our analyses $\boldsymbol{r_{min}}$ and $\boldsymbol{r_{in}}$ are set at 0%, and the battery SOC level is limited between 0% and 0%+DOD to form a basis when comparing different scenarios with and without BESS under the different DOD limits.

Based on Table 4.3, as DOD decreases, Ncycle increases. However, the same may not be true for battery lifetime throughput, which can decrease despite the decrease in DOD. Due to its nature, the model can assign very large values to E_{max}^{b} when it is not restricted, but since these values are not applicable for the farm, an upper limit of E_{max}^{b} is determined. Firstly, when all power is supplied by using only a battery, the required battery capacity to inject the maximum energy that the farm is allowed to supply to the grid in an hour is analyzed then, it is preferred to determine this upper limit, $MCAP$ by using 4 times this capacity. Equation 4.3 shows the calculation and gives 101 as $MCAP$

value. However, not all of the analyses in this study are performed with the $MCAP$ value 101, there are also analyses performed under different $MCAP$ values.

Table 4.3: DOD and Ncycle Relationship

DOD	**Ncycle**	**DOD*Ncycle**
60%	7356	4413.6
50%	9779	4889.5
40%	13367	5346.8
30%	19090	5727
20%	29532	5906.4
10%	55541	5554.1

$$MCAP = WFP/\eta^d \times 4 \qquad (4.3)$$

Table 4.4 shows the farm maximized profit with optimal battery rated power and rated energy capacity in Case 1 for each scenario generated with different BESS cost reduction rates, determination methods of committed energy amount in DAM and DOD limits. In the presence of a BESS, the farm can act more flexibly when determining $\boldsymbol{P_t^{com}}$ to take the advantage of factors such as price fluctuations. Unlike the situation without BESS, farm can have more chance to determine $\boldsymbol{P_t^{com}}$ different from $\boldsymbol{P_t^{F\prime}}$. In the current system, $\boldsymbol{P_t^{com}}$ is quite impactful on the profit and how it is determined is important. In the analyses, the change in the profit is examined by determining $\boldsymbol{P_t^{com}}$ value under different assumptions. $\boldsymbol{r_{min}}$ and $\boldsymbol{r_{in}}$ are set at 0%, $MCAP$ is 101, and M is a very large number for the analyses in the Table 4.4, 4.5, and 4.6.

Table 4.4: Maximized profit of the farm with optimal BESS capacity under the different scenarios in Case 1

$\boldsymbol{m_u = 2}$				
	$DOD = 0.6$		$DOD = 0.5$	
47%	3 502 301$	10.995MW-101MWh	3 510 542$	11.808MW-101MWh
32%	3 478 507$	9.305MW- 101MWh	3 485 072$	9.708MW-101MWh
16%	3 466 798$	7.668MW-101MWh	3 470 630$	7.916MW-101MWh
0%	3 461 412$	7.310MW-100MWh	3 463 537$	6.817MW-100MWh
$\boldsymbol{m_u = 2}$				
	$DOD = 0.4$		$DOD = 0.3$	
47%	3 515 880$	11.850MW-101MWh	3 515 997$	11.991MW-101MWh
32%	3 490 406$	10.099MW-101MWh	3 492 436$	10.100MW-101MWh
16%	3 474 155$	8.225MW-101MWh	3 476 220$	8.149MW-101MWh
0%	3 465 967$	7.525MW-101MWh	3 467 464$	7.583MW-101MWh
$\boldsymbol{m_u = 2}$				
	$DOD = 0.2$		$DOD = 0.1$	
47%	3 508 173$	10.100MW-101MWh	3 487 618$	10.055MW-101MWh
32%	3 488 870$	10.100MW-101MWh	3 475 378$	7.504MW-100MWh
16%	3 474 725$	8.149MW-101MWh	3 466 969$	5.518MW-101MWh
0%	3 466 745$	7.025MW-101MWh	3 462 402$	5.116MW-101MWh
$\boldsymbol{m_u = \mathrm{M}}$				
	$DOD = 0.5$		$DOD = 0.3$	
47%	3 516 659$	12.330MW-101MWh	3 522 068$	12.399MW-101MWh
32%	3 490 940$	10.037MW-101MWh	3 498 483$	10.287MW-101MWh
16%	3 476 393$	8.263MW-101MWh	3 482 286$	8.486MW-101MWh
0%	3 469 523$	7.539MW-101MWh	3 473 548$	7.663MW-101MWh
$\boldsymbol{P_t^{com} = P_t^{F'}}$				
	$DOD = 0.5$		$DOD = 0.3$	
47%	3 429 652$	10.510MW-101MWh	3 432 926$	10.287MW-101MWh
0%	3 381 786$	6.533MW-100MWh	3 387 383$	6.775MW-101MWh
$\boldsymbol{P_t^{com} = P_t^{W'}}$				

	$DOD = 0.5$		$DOD = 0.3$	
47%	3 494 884$	12.625MW-101MWh	3 498 176$	12.546MW-101MWh
0%	3 467 529$	7.916MW-101MWh	3 469 888$	7.539MW-99MWh

It is observed that the profit increased as the examined DOD limit value decreased between 60% and 30% under the same BESS cost scenario by the analyses for $\boldsymbol{m_u}$=2 in Table 4.4. Because in these DOD values, while DOD value decreases, battery lifetime throughput increases for any battery capacity. Although the battery lifetime throughput value of 20% DOD is higher than 30% DOD for a specified capacity, it could not give better results compared to 30% DOD in the specified range due to MCAP. Only when MCAP was increased to very high levels that are not preferable for the farm, 20% DOD limit was able to provide better results than 30% DOD limit by the analyses. Hence most of our analyses depend on 30% DOD limit value.

In the absence of a BESS, the farm determines $\boldsymbol{P_t^{com}}$ equal to $\boldsymbol{P_t^{F\prime}}$ and participates in the market. This farm manages to exceed its profit in this condition for Case 1 which is also shared in Table 4.2 by a significant amount in each scenario given in Table 4.4. This shows that these scenarios generated in Case 1 can increase the profit with BESS integration above the profit obtained in the absence of a BESS. The profit that the farm without BESS would make in the situation $\boldsymbol{P_t^{com} = P_t^{W\prime}}$ for Case 1 shared in Table 4.2 where the farm participates in the market in the absence of a BESS by making a perfect production forecast can be exceeded by the different scenarios with BESS as seen in Table 4.4. $\boldsymbol{P_t^{com} = P_t^{W\prime}}$ setting is selected in the presence of BESS for case 1 to analyze the model behavior, it is seen that the model solution bears the imbalance and degradation costs in order to benefit from price fluctuations and improves the profit compared to $\boldsymbol{P_t^{com} = P_t^{W\prime}}$ scenario for the farm without BESS in Case 1. The positive impact of a decrease in BESS cost or increase in the value of $\boldsymbol{m_u}$ on profit can be discerned from the Table 4.4.

Considering the way $\boldsymbol{P_t^{com}}$ is determined, for $\boldsymbol{m_u}$= **M** and $\boldsymbol{P_t^{com}} = \boldsymbol{P_t^{W\prime}}$ scenarios if the model chooses to use BESS, the profit obtained should not be less than $\boldsymbol{P_t^{com}} = \boldsymbol{P_t^{W\prime}}$ scenario profit of the situation without BESS in the analyses for each of three cases. It can be seen in Table 4.4, 4.5, and 4.6 that analysis results meet this condition and are consistent. In some cases, the model solution may determine values for the rated power and rated energy capacity of the battery as very close to zero or as a significant amount and not use the battery at all since in the model the degradation cost of BESS occurs when only the battery is used. In these cases, results are accepted as no battery solution and transferred to tables in this way.

Table 4.5: Maximized profit of the farm with optimal BESS capacity under the different scenarios in Case 2

$\boldsymbol{m_u = 2}$				
	$DOD = 0.5$		$DOD = 0.3$	
47%	3 427 599$	7.492MW-101MWh	3 427 909$	8.402MW-101MWh
0%	3 426 854$	0.497MW-101MWh	3 426 872$	2.480MW-96MWh
$\boldsymbol{m_u} =$ **M**				
	$DOD = 0.5$		$DOD = 0.3$	
47%	3 434 207$	No battery	3 434 207$	No battery
0%	3 434 207$	No battery	3 434 207$	No battery
$\boldsymbol{P_t^{com} = P_t^{F\prime}}$				
	$DOD = 0.5$		$DOD = 0.3$	
47%	3 353 724$	8.437MW-101MWh	3 355 867$	7.575MW-101MWh
0%	3 341 803$	5.589MW-101MWh	3 343 750$	5.762MW-101MWh
$\boldsymbol{P_t^{com} = P_t^{W\prime}}$				
	$DOD = 0.5$		$DOD = 0.3$	
47%	3 434 207$	No battery	3 434 207$	No battery
0%	3 434 207$	No battery	3 434 207$	No battery

In case 2, where the impact of MCP fluctuation on the profit is less than other cases, the use of BESS results in smaller profit increase compared to BESS use in Case 1 under same scenarios in the analysis. Table 4.5 illustrates that utilizing BESS increases the farm's profit compared to $\boldsymbol{P_t^{com}} = \boldsymbol{P_t^{F\prime}}$ scenario profit of the situation without BESS in Case 2. When Table 4.5 is examined, it is seen that no battery is assigned for some scenarios where battery usage cannot increase profit of the farm.

Table 4.6: Maximized profit of the farm with optimal BESS capacity under the different scenarios in Case 3

$\boldsymbol{m_u = 2}$				
	$DOD = 0.5$		$DOD = 0.3$	
47%	3 751 067$	7.492MW-101MWh	3 751 411$	8.469MW-101MWh
0%	3 748 855$	7.492MW-101MWh	3 749 227$	7.352MW-101MWh
$\boldsymbol{m_u = M}$				
	$DOD = 0.5$		$DOD = 0.3$	
47%	3 755 833$	No battery	3 755 833$	No battery
0%	3 755 833$	No battery	3 755 833$	No battery
$\boldsymbol{P_t^{com} = P_t^{F\prime}}$				
	$DOD = 0.5$		$DOD = 0.3$	
47%	3 680 105$	7.834MW-101MWh	3 683 238$	7.087MW-101MWh
0%	3 662 824$	5.762MW- 86.673MWh	3 665 540$	6.109MW-101MWh
$\boldsymbol{P_t^{com} = P_t^{W\prime}}$				
	$DOD = 0.5$		$DOD = 0.3$	
47%	3 755 833$	No battery	3 755 833$	No battery
0%	3 755 833$	No battery	3 755 833$	No battery

For Case 3, using BESS increases the farm's profit compared to $\boldsymbol{P_t^{com}} = \boldsymbol{P_t^{F\prime}}$ scenario profit of the situation without BESS. In Case 3, where the impact of MCP fluctuation on profit is less than Case 1, the use of BESS results in a less profit increase compared to

BESS use in Case 1 under the same scenario of the analysis. However, profit of Case 3 is higher than Case 1 profit in the presence of a BESS according to analysis results. Some scenarios give no battery solution for Case 3 as seen in Table 4.6. BESS integration can not enhance the farm's profit for these scenarios.

Table 4.7: Maximized profit of the farm with optimal BESS capacity under various $MCAP$ values

$P_t^{com} = P_t^{F\prime}$ $DOD = 0.3$ 0% BESS cost reduction		
Case 1	3 367 129$ 0.015MW-0.1MWh	3 375 076$ 2.307MW-20MWh
Case 2	3 338 467$ 0.750MW- 5MWh	3 337 430$ 0.015MW-0.1MWh
Case 3	3 659 055$ 0.015MW-0.1MWh	3 662 077$ 2.012MW-20MWh
$m_u =$ M $DOD = 0.3$ 0% BESS cost reduction		
Case 1	3 466 483$ 2MW-20MWh	3 464 615$ 0.507MW-5MWh
Case 2	3 434 207$ No battery	3 434 207$ No battery
Case 3	3 755 833$ No battery	3 755 833$ No battery

When $MCAP$ takes different values below 101, obtained rated power and rated energy capacity of battery and farm's profit are shared in Table 4.7. This table demonstrates that utilizing BESS can enhance the farm's profit compared to $\boldsymbol{P_t^{com}} = \boldsymbol{P_t^{F\prime}}$ scenario profit of the situation without BESS for different $MCAP$ values below 101.

$$P_t^{c\prime} = P_t^c \times \eta^c \tag{4.4}$$

$$P_t^{d\prime} = P_t^d / \eta^d \tag{4.5}$$

For the Case 1, where $\boldsymbol{m_u} = M$, $\boldsymbol{r_{in}} = 0.3$, $\boldsymbol{r_{min}} = 0.3$, and $DOD = 0.3$ under the current BESS cost, optimization results are demonstrated with Figure 4.1 and Figure 4.2 where $P^{c\prime}$ is the power charged to battery (after losses) and $P^{d\prime}$is power discharged by the battery (before losses) as they are explained with Equation 4.4 and Equation 4.5, respectively. In this analysis battery rated energy capacity and rated power are found as 63.35 MWh and 19MW, respectively.

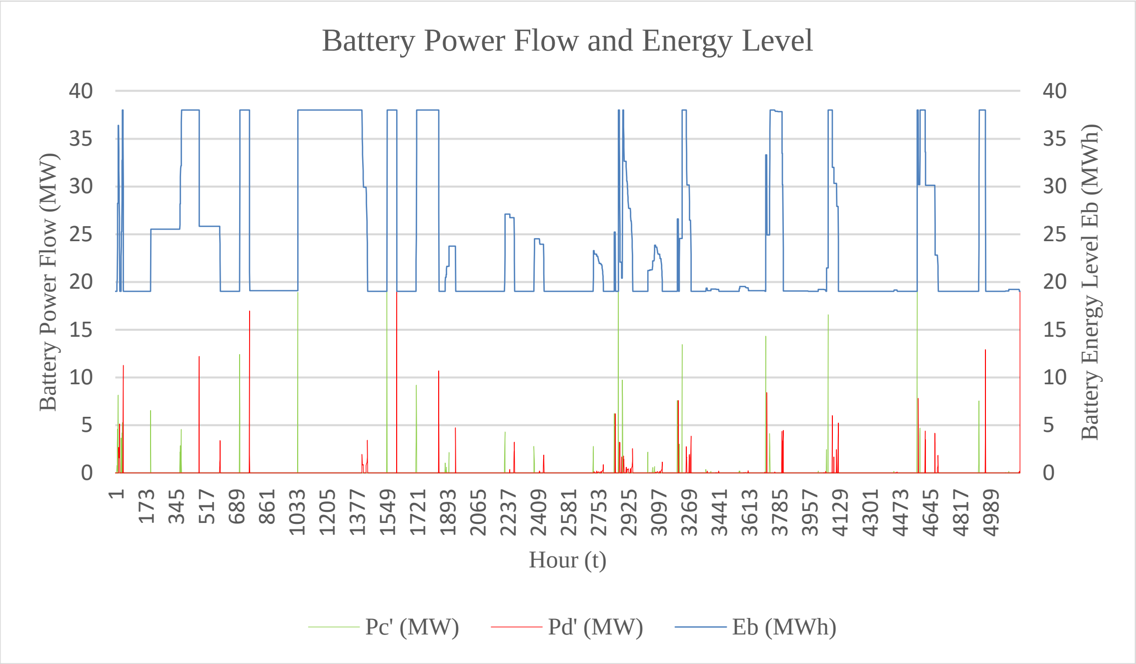

Figure 4.1: Battery power flow and energy level for Case 1

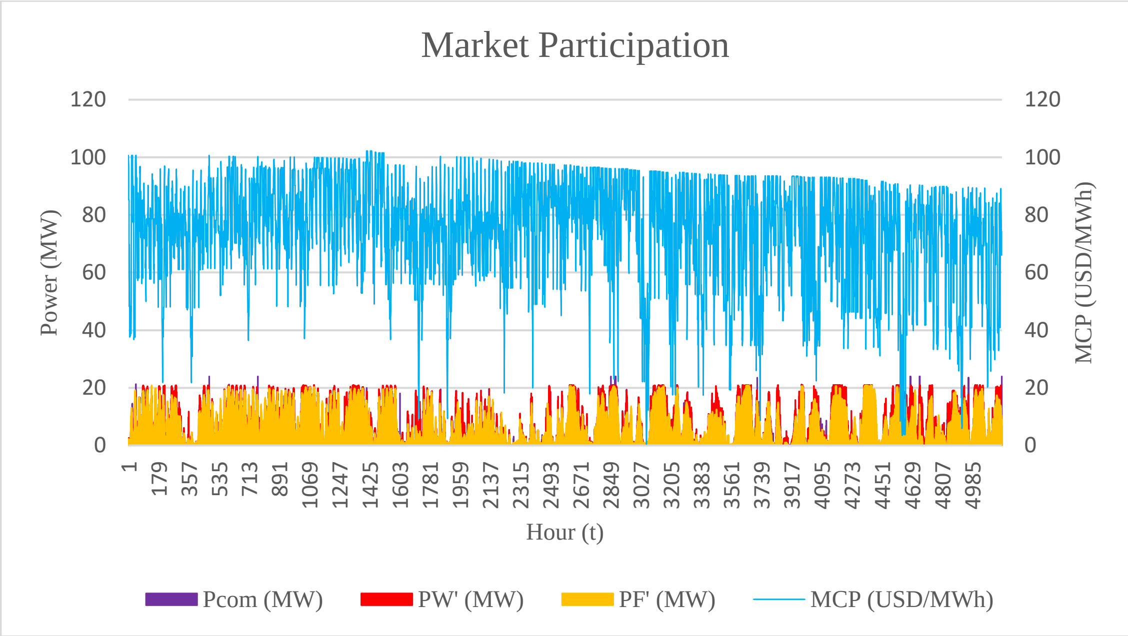

Figure 4.2: Market participation in Case 1

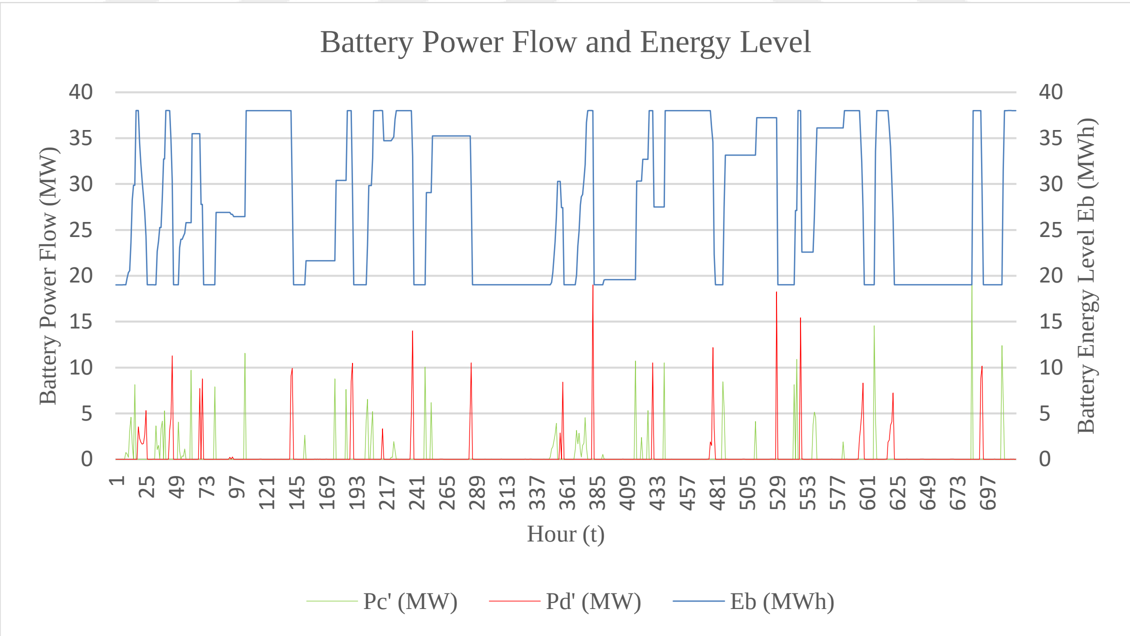

Figure 4.3: Battery power flow and energy level for Case 1 in 47% BESS cost reduction

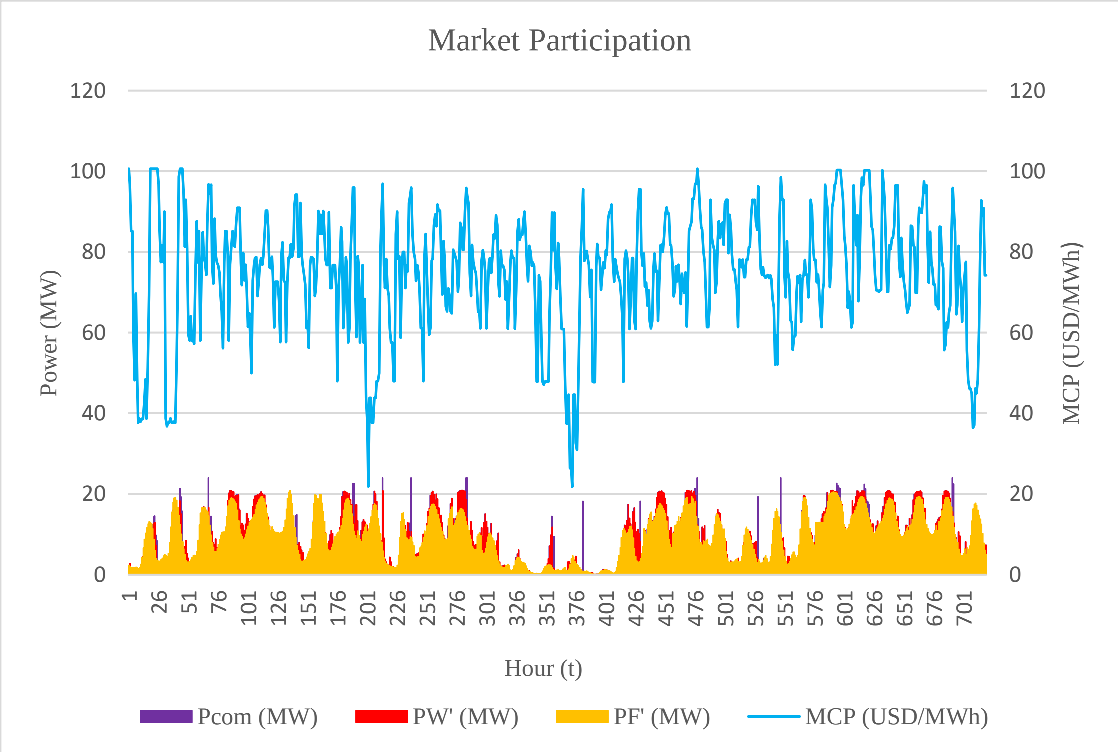

Figure 4.4: Market participation in Case 1 for 47% BESS cost reduction

For Case 1, where $\boldsymbol{m_u} = M$, $\boldsymbol{r_{in}} = 0.3$, $\boldsymbol{r_{min}} = 0.3$, and $DOD = 0.3$ under the 47% BESS cost reduction scenario, optimization results are illustrated with Figure 4.3 and Figure 4.4 by showing only first month. Battery rated energy capacity is determined as 63.35 MWh with this analysis.

For Case 2, where $P_t^{com} = P_t^{F\prime}$,$\boldsymbol{r_{in}} = 0.3$, $\boldsymbol{r_{min}} = 0.3$, and $DOD = 0.3$ under the current BESS cost, optimization results are depicted in Figure 4.5 and Figure 4.6. This analysis results in 63.35 MWh for battery rated energy capacity. Only first month is shared by Figure 4.6.

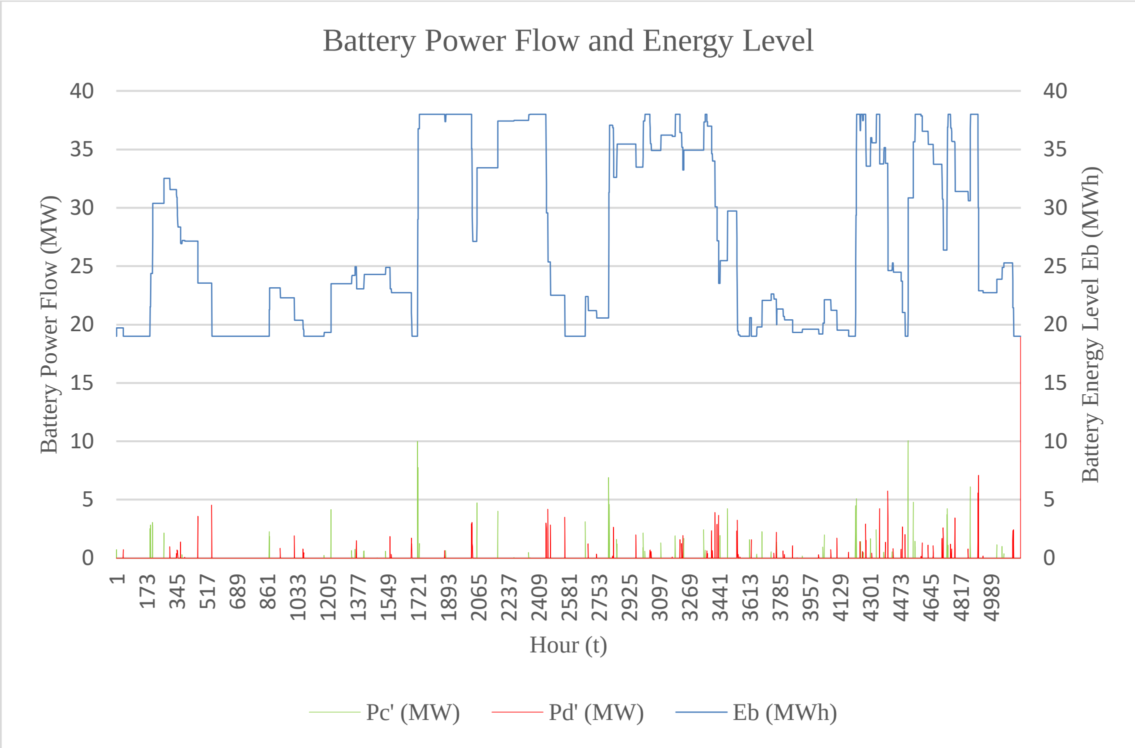

Figure 4.5: Battery power flow and energy level for Case 2

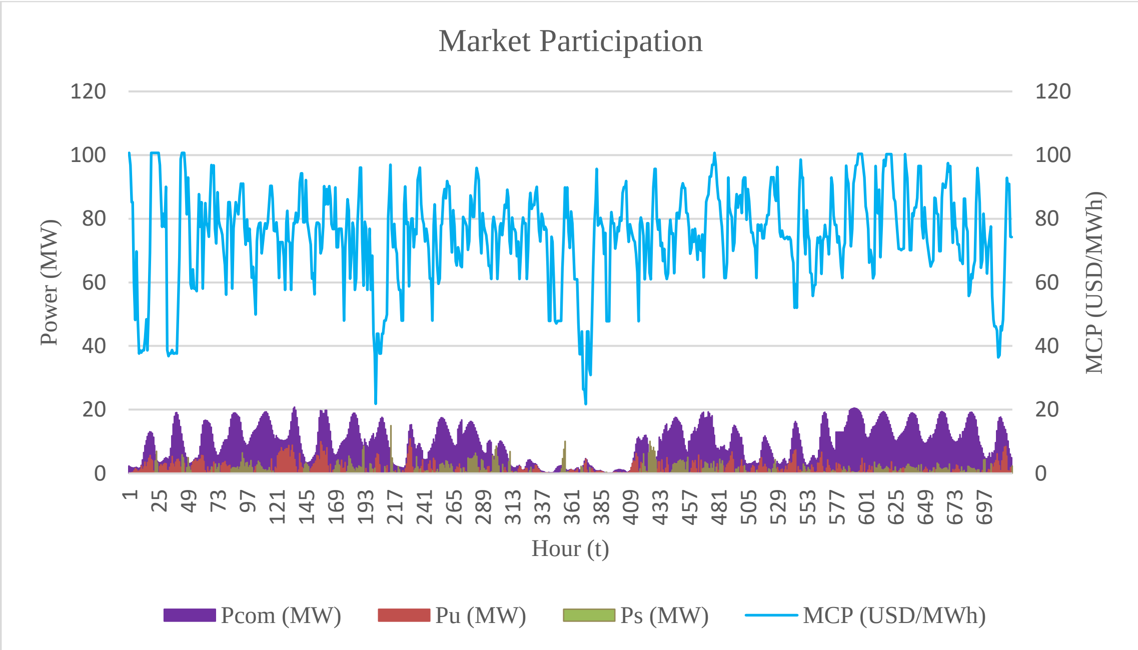

Figure 4.6: Market participation in Case 2

For Case 3, where $\boldsymbol{m_u} = 2$, $\boldsymbol{r_{in}} = 0.3$, $\boldsymbol{r_{min}} = 0.3$, and $DOD = 0.3$ under the current BESS cost, optimization results are demonstrated with Figure 4.7 and Figure 4.8. In this analysis battery rated energy capacity is found as 63.35 MWh.

When the figures describing the optimization results of different scenarios are examined, it can be seen that P_t^u and P_t^s don't take positive values at the same time in these analyses and charging and discharging of BESS does not occur simultaneously at any time t. Figure 4.6 and Figure 4.8 illustrate that energy imbalance can happen in $P_t^{com} = P_t^{F\prime}$ and $\boldsymbol{m_u} = 2$ scenarios since the model is quite restricted while determining P_t^{com}.

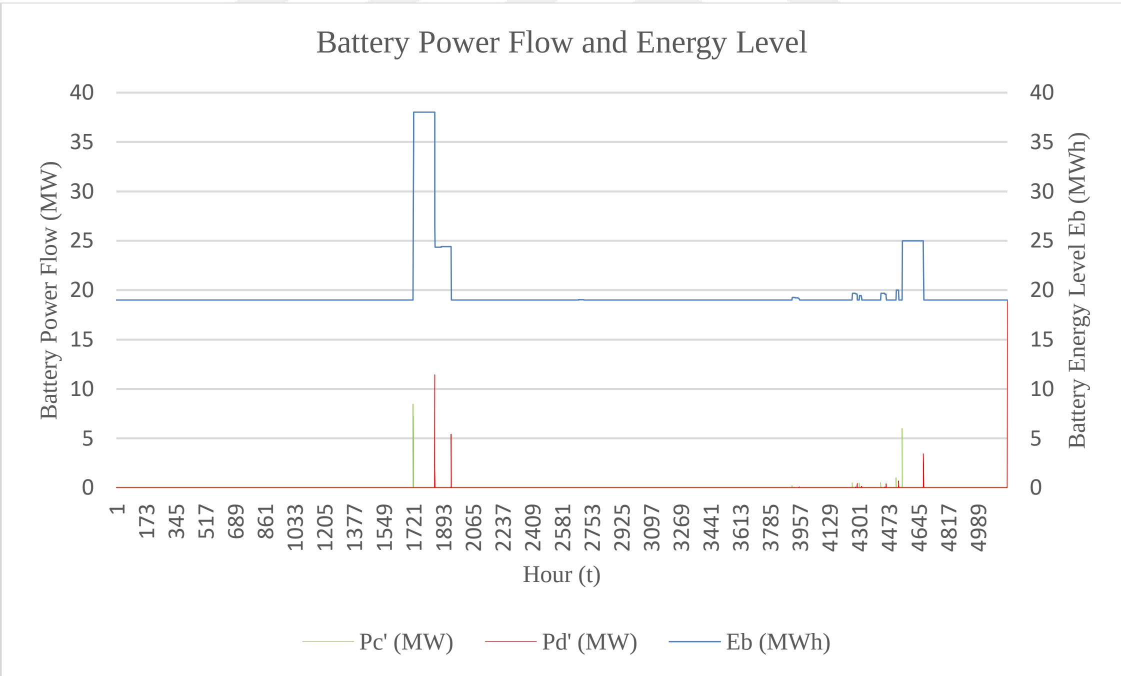

Figure 4.7: Battery power flow and energy level for Case 3

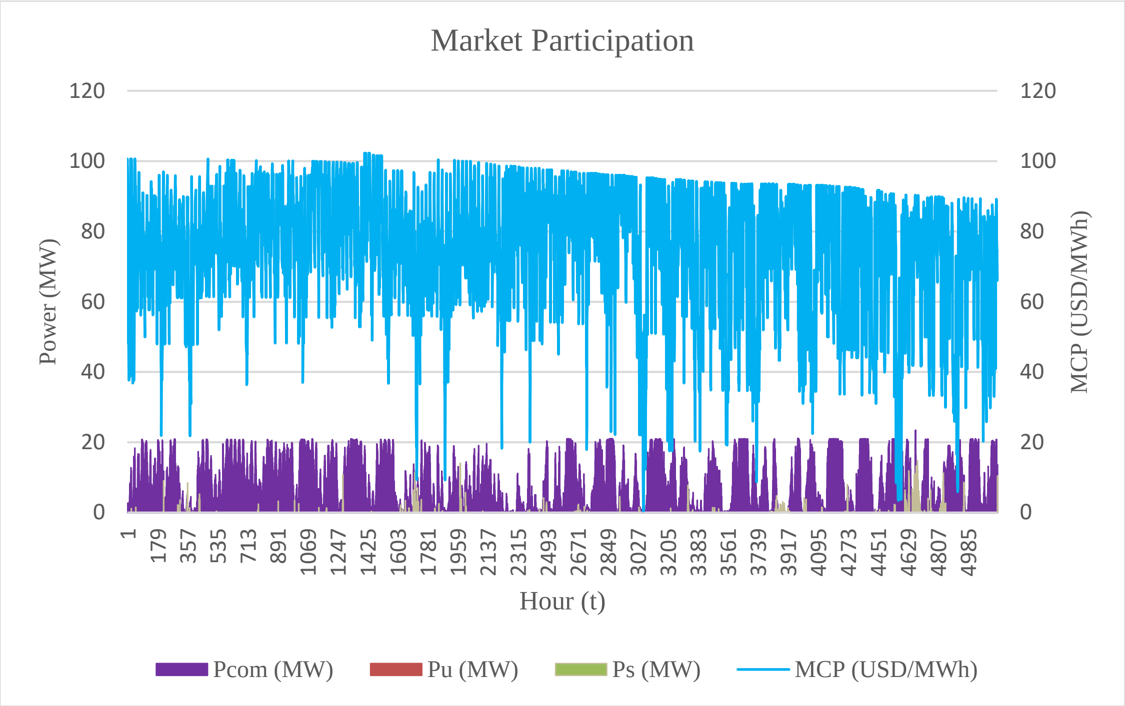

Figure 4.8: Market participation in Case 3

5. CONCLUSION

Market price fluctuations and imbalance costs make energy storage systems preferable for power generation facilities. These storage systems can be more meaningful for the intermittent RESs such as wind energy. Within the scope of this thesis, an onshore wind farm with an installed power capacity of 24 MW in Türkiye has been examined. This farm continues to benefit from the initial YEKDEM tariff but considers participating in DAM by leaving YEKDEM since MCP has exceeded the YEKDEM tariff price more frequently especially over the past year. A more attractive incentive scenario than the initial YEKDEM tariff is suggested in this study and three different market participation cases including Cases 1, 2, and 3 are analyzed. Case 1 denotes participating in DAM by leaving YEKDEM while Cases 2 and 3 denote participating in DAM with actual and suggested YEKDEM tariff, respectively. A nonlinear optimization model that includes the degradation cost of BESS is developed to maximize wind farm’s profit by optimal BESS sizing and operation scheduling. The impact of BESS integration on the farm's profitability is investigated for three market participation cases with data of a 7-month period experienced by this farm. Using the IPOPT solver in GAMS, scenarios with varying DOD limit values, determination methods of committed energy amount in DAM and BESS costs are solved. The results show that even a BESS with 0.1 MWh battery rated energy capacity can enhance farm's profit under the current BESS cost and market conditions for each of the three market participation cases. It is observed that greater profit increases are achieved by different battery capacities above 0.1 MWh. To examine the effect of DOD limit value on profit, some analyses are repeated by changing only this value and it is discovered that DOD limit value of 0.3 increases the profit the most. According to analysis results, there are scenarios where BESS integration can not enhance farm’s profit, so optimal solution is found as no battery for them. When the profit of the situations with and without BESS is compared under a scenario, the market participation case that provides the greatest profit difference between the two situations by BESS integration for the scenario is Case 1 where MCP fluctuations have higher impact on the farm's profit comparing to other participation cases. When the profits generated in three different cases for the same scenario as a result of BESS integration are evaluated, it is seen that the highest profit is obtained in Case 3 while the lowest profit is obtained in Case 2. Considering the analysis results, under the current market conditions and in the presence of a BESS, participating in DAM by leaving YEKDEM is more advantageous for the farm compared to the actual YEKDEM tariff but if the suggested incentive scenario is implemented by authorities, YEKDEM becomes the best alternative for the farm's market participation.

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